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Humanoid Balancing on Unstable Terrain Using Whole-Body Momentum Control and Series Elastic Actuation

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Abstract— **This video presents early results for dynamic balancing on unstable terrain using THOR, a 34-DoF torque-controlled humanoid. The proposed stance controller stabilizes the centroidal dynamics by regulating the Divergent Component of Motion (DCM) using whole-body momentum control. A quadratic program (QP) is used to compute optimal joint torques given desired task-space objectives and frictional contact constraints. Joint setpoints are tracked using "simple" impedance control to enable compliant balancing on uneven and non-stationary surfaces. High fidelity force control is made possible through the use of low impedance series elastic actuators in the lower body. We test THOR's ability to recover from disturbance forces and track desired DCM reference trajectories during stance. We also demonstrate balancing on unstable terrain using a platform that rotates and translates about a pivot.**

I. SUMMARY

This video presents early results for dynamic balancing on unstable terrain using the THOR platform. THOR, the Tactical Hazardous Operations Robot, is a compliant 34-DoF humanoid robot developed through the DARPA Robotics Challenge and ONR Shipboard Autonomous Firefighting Robot (SAFFiR) program. In order to enable mobility in disaster relief areas and shipboard environments, we are researching locomotion strategies on unstructured and non-stationary terrain. The video demonstrates compliant balance control using a model-based whole-body momentum controller. We include footage of THOR recovering from external disturbances during stance and balancing on a moving platform that rotates and translates about a pivot.

The THOR lower body is equipped with linear series elastic actuators with inline load cells to enable low impedance force control. Joint trajectories are tracked using a "simple" joint impedance controller with feedforward torque compensation. Absolute encoders are included at each joint for position and velocity estimation, and an Attitude and Heading Reference Sensor (AHRS) is mounted to the torso link to provide inertial measurements of the floating base frame. Model-based state estimation and control is implemented using a 30-DoF rigid body model obtained from CAD.

Inspired by [1] [2] [3], we implement a model-based whole-body controller to optimize desired joint accelerations and contact forces using a linearly constrained quadratic program (QP) in the form,

$$\min_{\ddot{\mathbf{q}},\boldsymbol{\rho}} \left\| \mathbf{C}_{\mathrm{b}} \left(\mathbf{b} - \dot{\mathbf{J}}\dot{\mathbf{q}} - \mathbf{J}\ddot{\mathbf{q}} \right) \right\|^2 + \lambda_{\ddot{\mathbf{q}}} \|\ddot{\mathbf{q}}\|^2 + \lambda_{\boldsymbol{\rho}} \|\boldsymbol{\rho}\|^2, \quad (1)$$

subject to the centroidal equations of motion, frictional contact constraints, and joint position and torque limits. Here $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ are the joint velocity and acceleration vectors, $\boldsymbol{\rho}$ is the vector of contact forces, $\mathbf{b}$ is the vector of task-space acceleration objectives and $\mathbf{J}$ is the corresponding matrix of stacked Jacobians. The semipositive-definite weighting matrix $\mathbf{Q}_{\mathrm{b}} = \mathbf{C}_{\mathrm{b}}^T \mathbf{C}_{\mathrm{b}}$ determines the relative priority of each task, and $\lambda_{\ddot{\mathbf{q}}}$ and $\lambda_{\boldsymbol{\rho}}$ provide input regularization.

To enable dynamic balancing, we regulate the Divergent Component of Motion (DCM) by tracking momentum rate of change objectives using the whole-body controller. The three-dimensional DCM [4] is a linear transformation of the center of mass (CoM) state that encodes the unstable component of the linear inverted pendulum dynamics. During stance, the DCM setpoint defines an equilibrium point for the CoM, nominally above the center of the support polygon. Cartesian and joint-space PID feedback is used to compute torso and arm acceleration objectives. By assigning lower QP weights to the angular momentum and upper body acceleration objectives, the stance controller is able to recover from large disturbance forces by "windmilling" the torso and arms to generate desired linear momentum rates of change.

The combination of whole-body momentum control and compliant joint control allows the robot to adapt to uncertain terrain by directly regulating internal forces. As shown in the final clip, this enables THOR to stand on a moving platform with no a priori knowledge of the surface dynamics.

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